Feasibility study of sub-10 nm half-pitch fabrication using chemically amplified resist processes of extreme ultraviolet lithography

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Two keywords in the development of resist materials and processes

Lithography roadmap

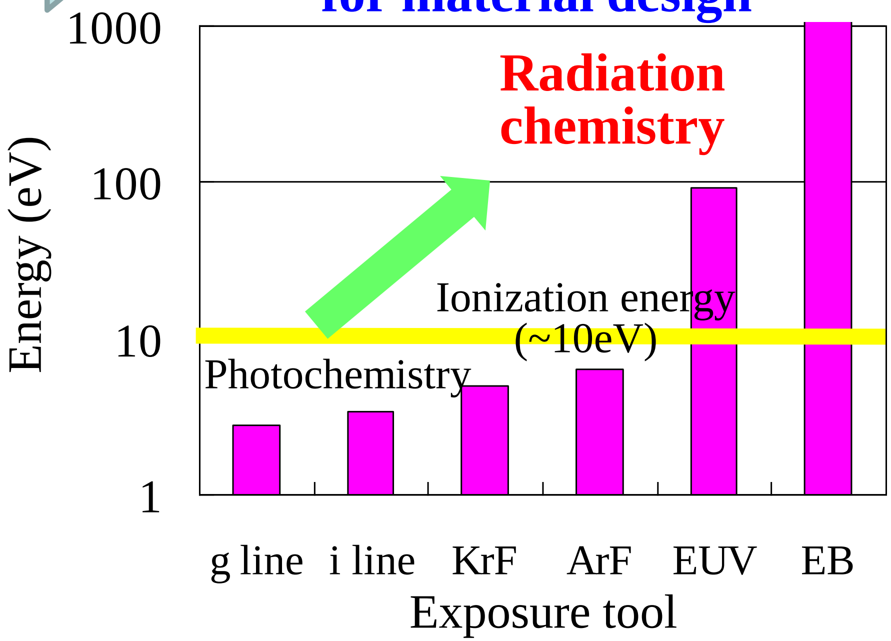
ITRS2010 Update

Year	2001	04	07	10	13	16	19	22
Line width (nm)	130	90	65	45	32	22	16	11
LWR (nm)					2.2	1.6	1.1	0.8

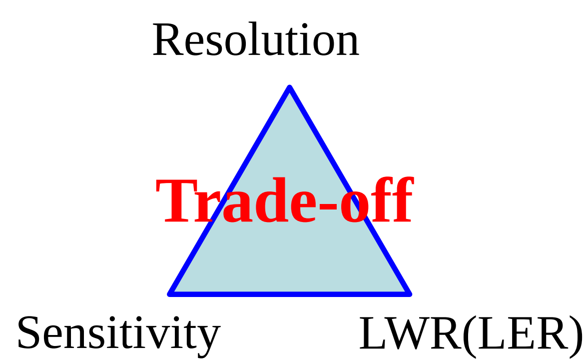
Lithography Solution

- KrF excimer (248 nm)
- ArF excimer (193 nm)
- ArF excimer Immersion (+DP)
- EUV (13.5 nm)
- EB for mask production

Change of basic science for material design



Trade-off relationships between resolution, sensitivity, and LER



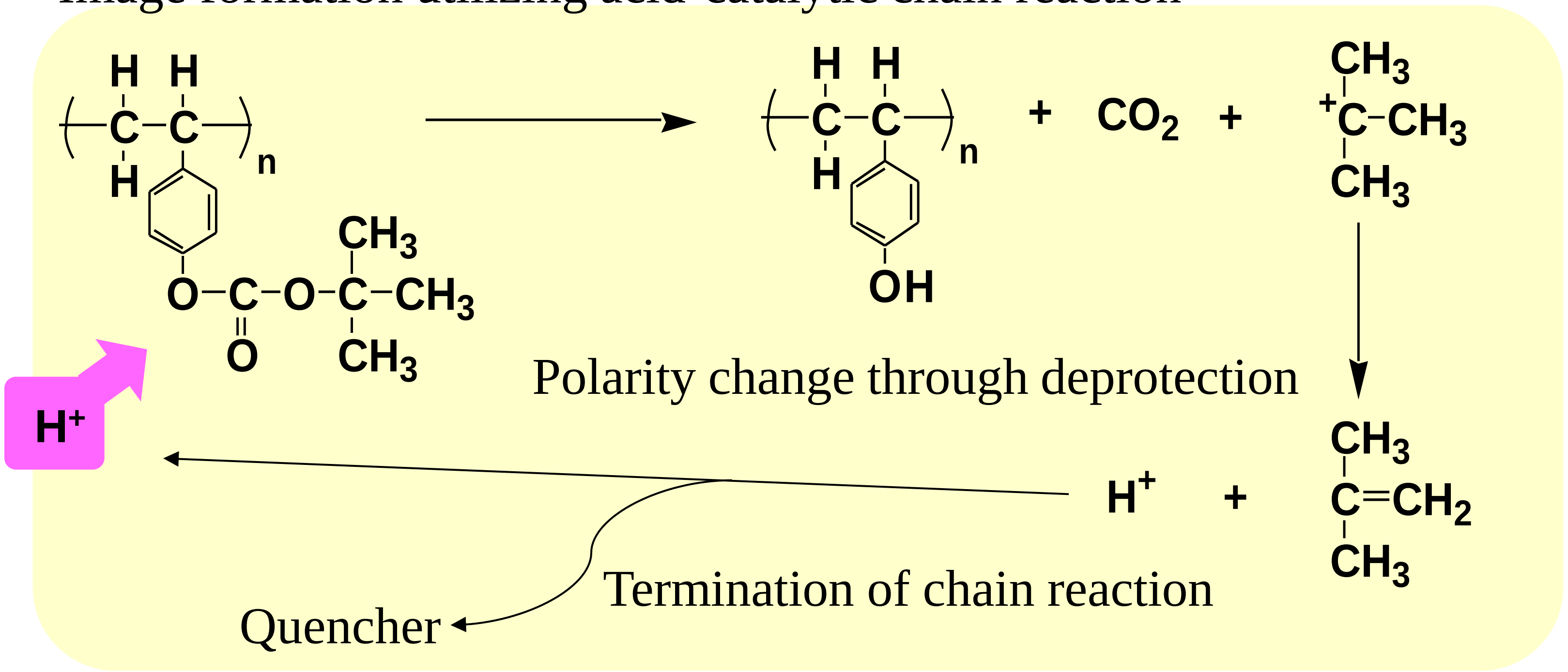
Concept of chemically amplified resist

Typical components: Partially protected polymer, Acid generator, Quencher

Acid generation through the decomposition of acid generators by exposure

$$Ph_3S^+X^- \xrightarrow{h\nu\text{、 radiation}} H^+X^-$$

Image formation utilizing acid-catalytic chain reaction



High sensitivity is obtained through acid-catalytic chain reaction.
High resolution is obtained through the control of acid diffusion using quenchers.

Role of resist materials

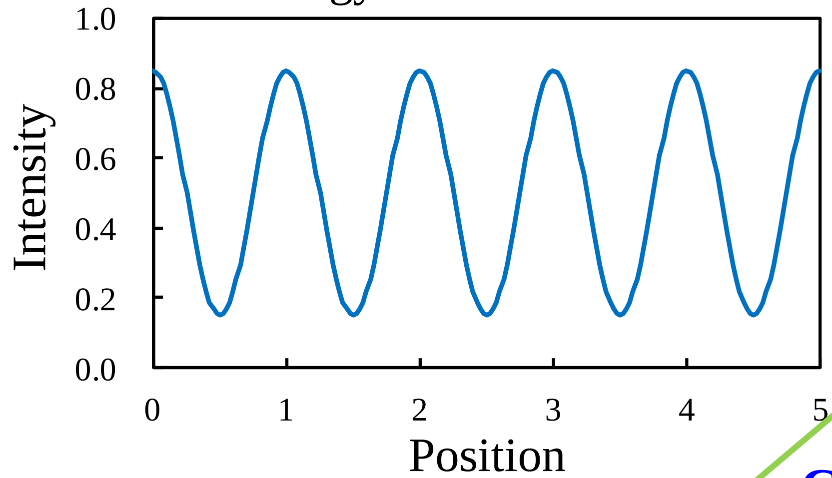
Conversion of energy modulation to binary image

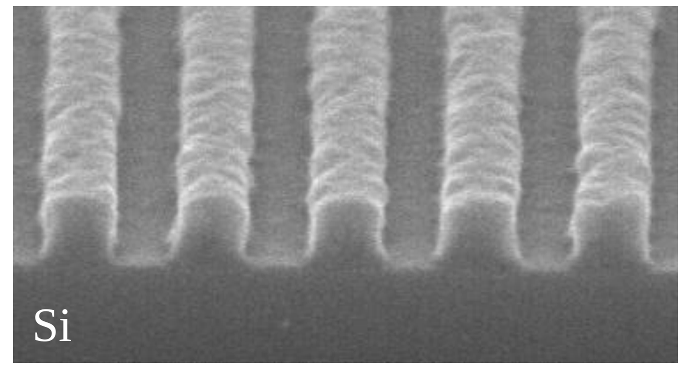
Exposure source

Role of photons:
Transfer of information and energy for imaging

Resist image

Energy modulation





SEM image of resist

Conversion process

Photon/electron interaction with matter

Thermal energy

Solubility change through chemical reaction

Dissolution of molecules

Energy deposition → Formation of acid image → Formation of latent image → Development

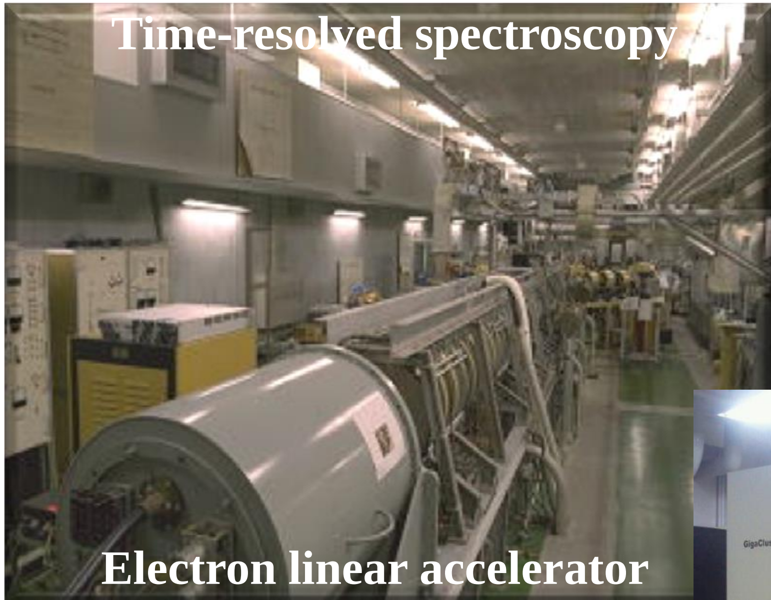
Decomposition of acid generator

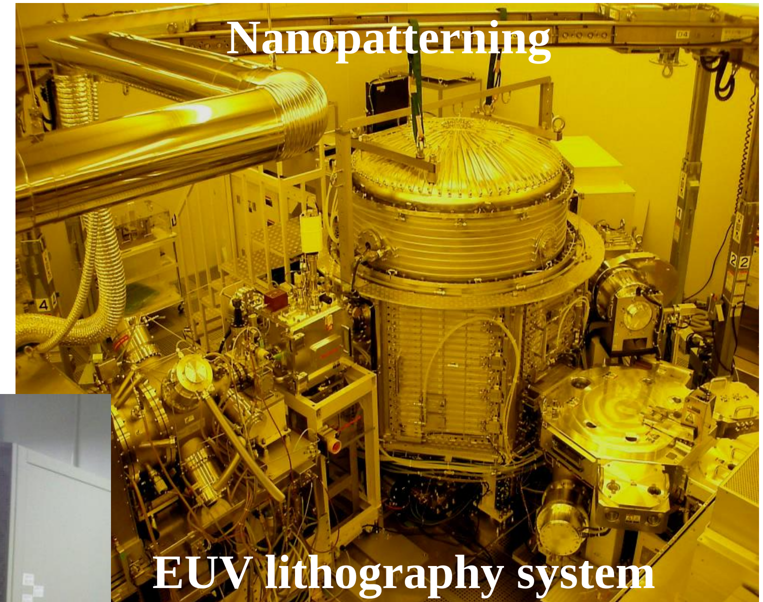
Acid diffusion, deprotection

Improvement of resist performance = Improvement of conversion efficiency

Objective

Establishment of scientific foundation and technology
for resist characterization of EUV lithography





Ultrashort electron beam

Time resolution **<1 ps**

Modeling

Change of basic science

600 cores

High-quality optical image

Spatial resolution **<20 nm**

Material information

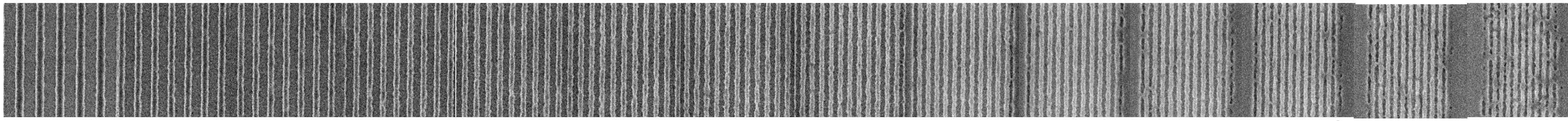
Trade-off relationships

Strategy of material design (sub-10 nm half-pitch fabrication)

Analysis of high performance resists (SSR3, 4, 5, 7 and ESR1)

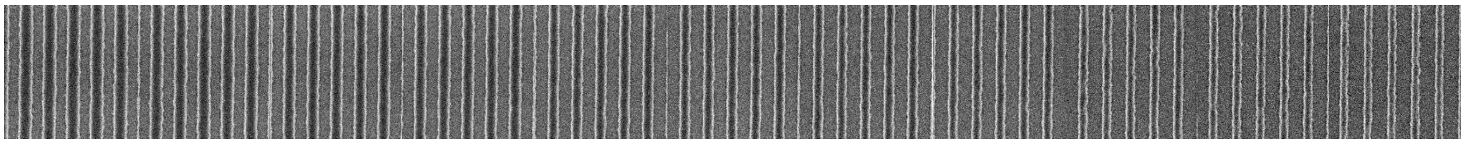
Half-pitch dependence (16 mJ cm^{-2} exposure dose) nm

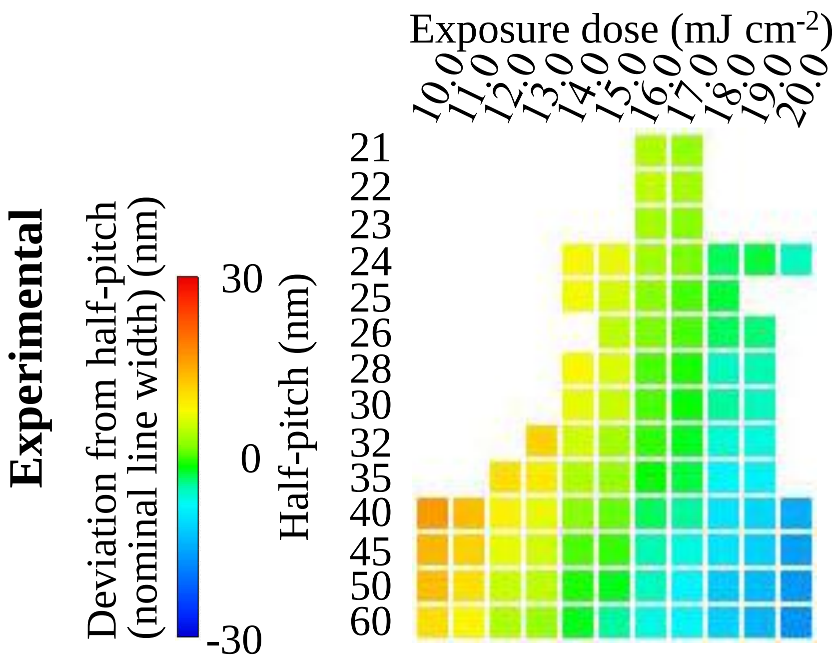
60 50 45 40 35 32 30 28 26 25 24 23 22 21



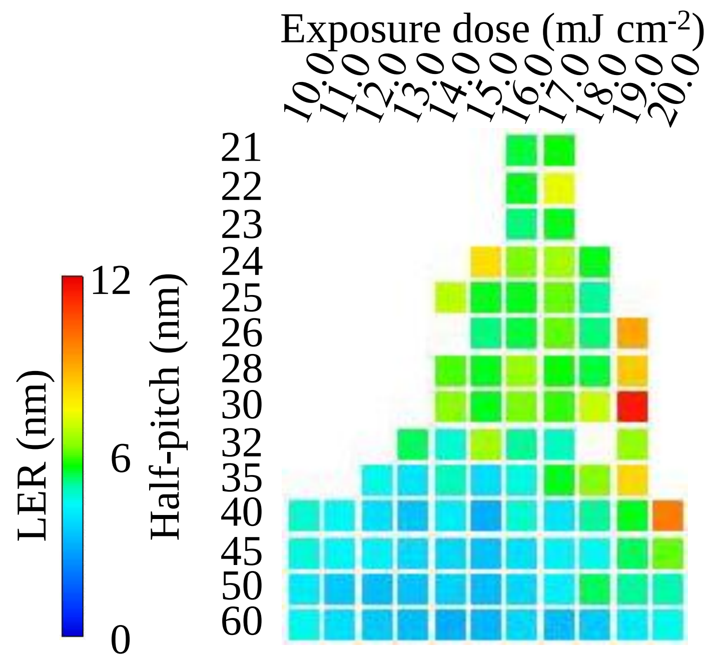
Exposure dose dependence (60 nm HP) mJ cm^{-2}

10 11 12 13 14 15 16 17 18 19 20





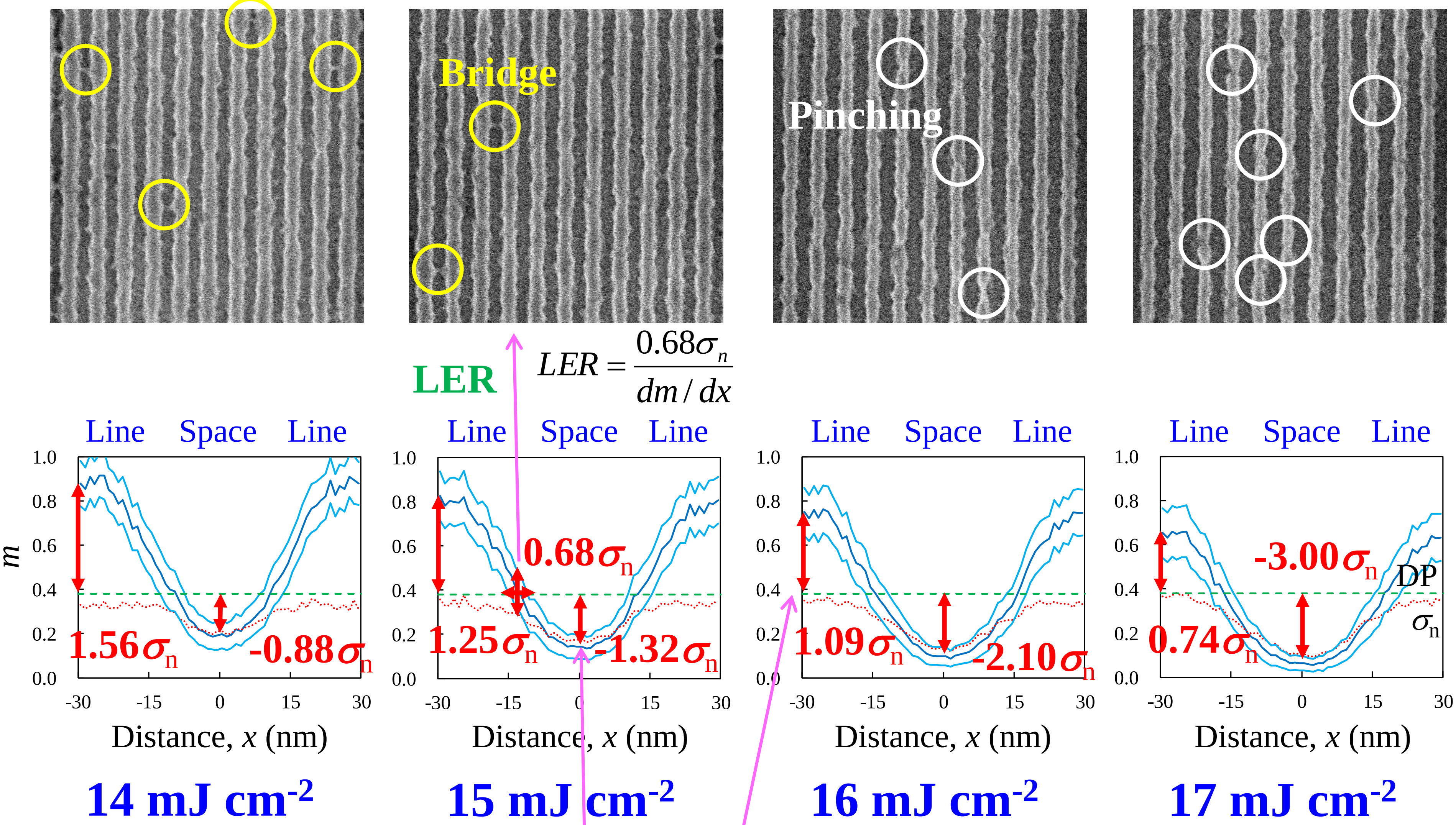
(a) Line width



(b) LER

Current status of the efficiency of conversion processes

Advanced resist characterization

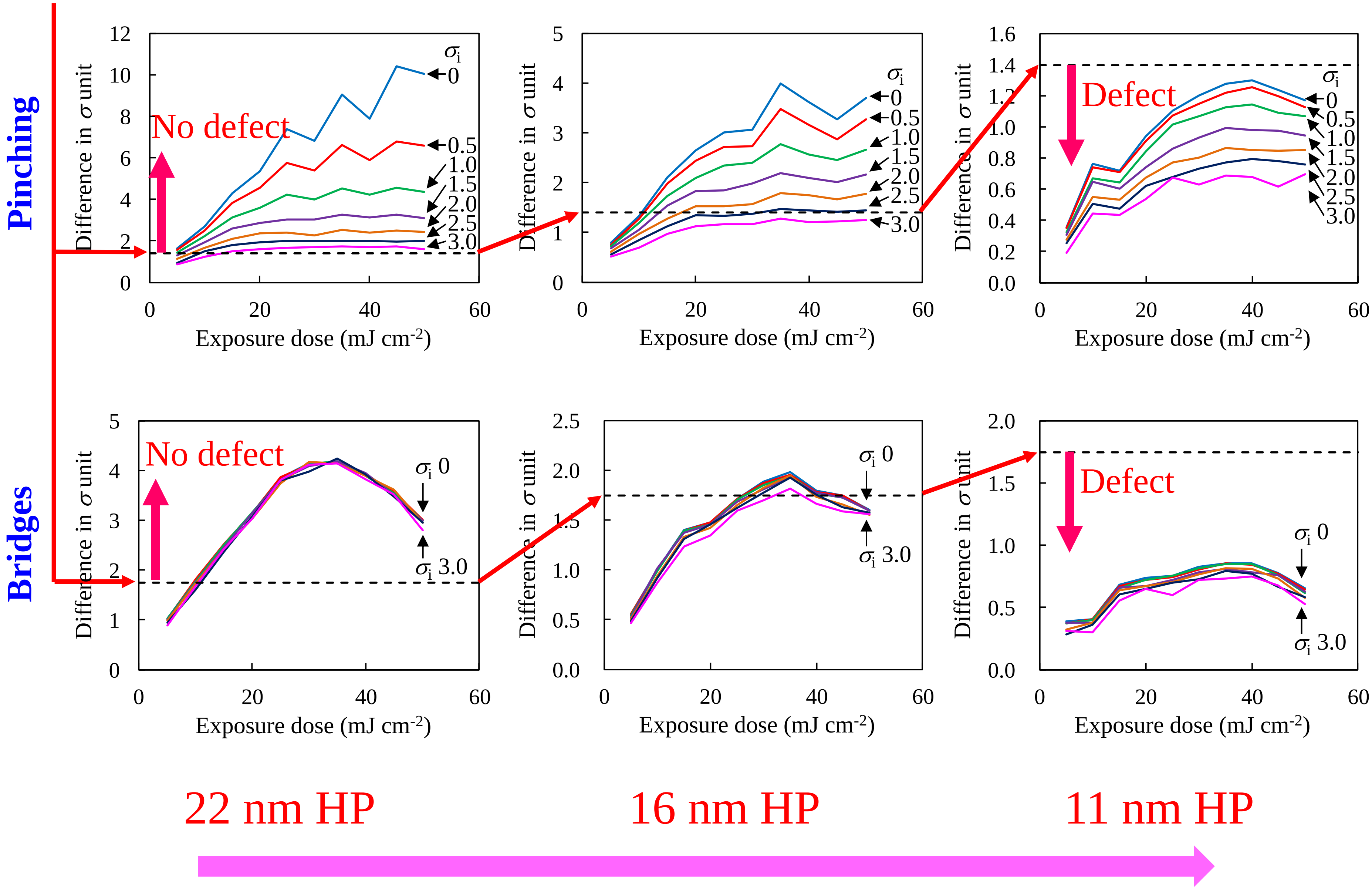


Stochastic defect generation

- Pinching started to appear.
- Bridges were eliminated.

Half pitch dependence of stochastic defect generation

Threshold for the elimination of stochastic defect generation in “a SEM image”



Probability for stochastic defect generation rapidly increased with the reduction of half-pitch.

Current status of the efficiency of conversion processes

①How many photons can be absorbed?

Absorption coefficient: ~4 /μm

②How many acids can be generated by a single photon?

Quantum efficiency: 2-3

③How many dissolution inhibitor (protecting group) can be removed by a single acid during the diffusion of unit length?

Effective reaction radius: 0.06-0.16 nm

- Activation energy for deprotection
- Activation energy for acid diffusion
  - Low-diffusion anion → Anion-bound resist
  - High T_g polymer

④How smoothly are the polymers dissolved in developer?

Relationship between LER and chemical gradient, f_{LER}: 0.14-0.31

- Molecular size, protection ratio, dispersion
- Development, rinse

Resist design

$$LER = \frac{0.68\sigma_n}{dm/dx}$$

dm/dx ← ①, ②, ③

	DUV, VUV	EUV
AG	①, ②, ③	②, ③
Polymer	③, ④	①, ②, ③, ④

Chemical gradient of 7 nm line-and-space patterns

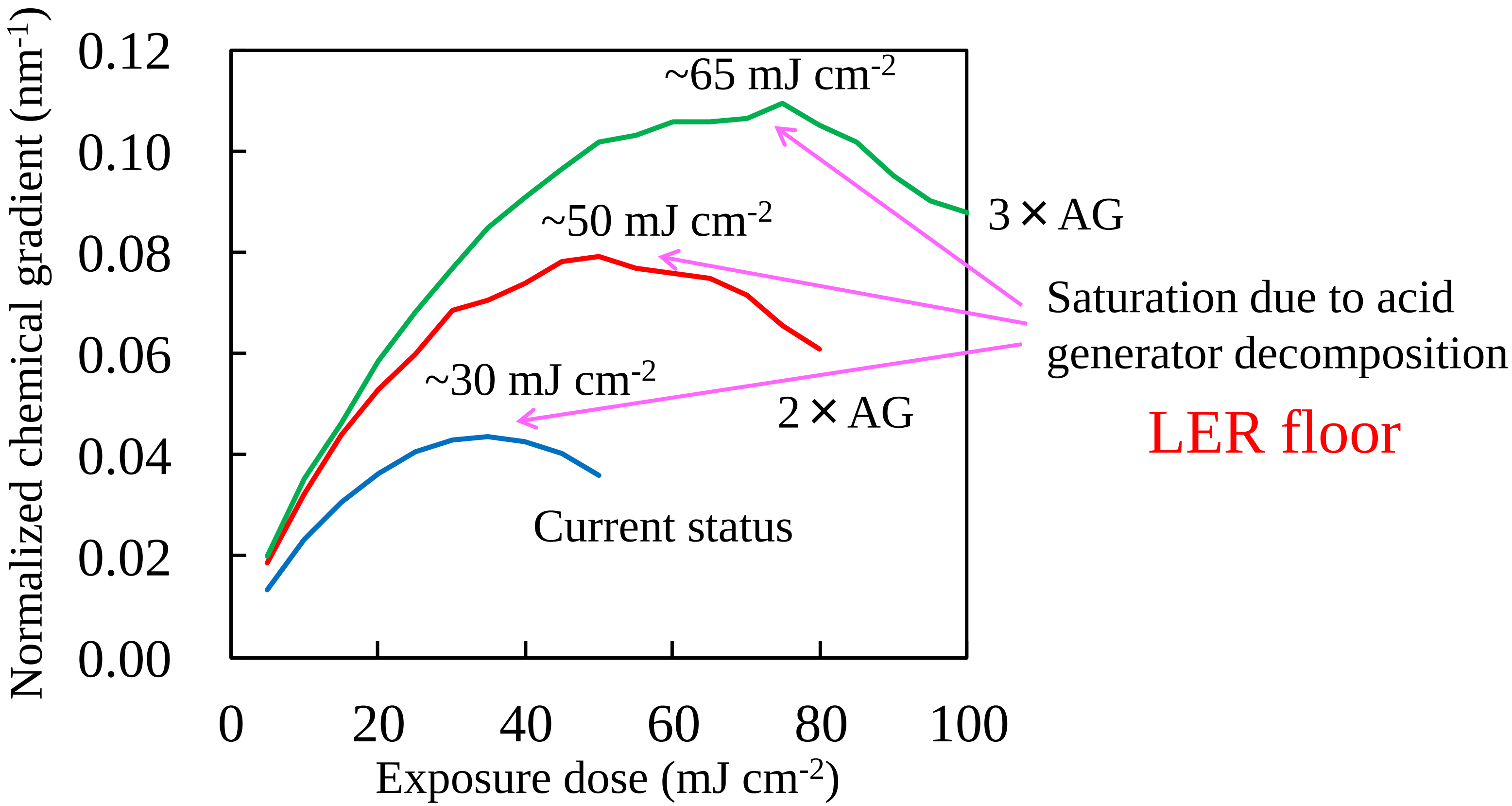


Fig. Exposure dose dependence of normalized chemical gradient of line-and-space patterns with half-pitch of 7 nm. The optical contrast was 1.0. The effective reaction radius for deprotection was 0.1 nm. The quencher concentration, PEB time, and dissolution point (the normalized protected unit concentration at half the depth of boundaries between lines and spaces) were optimized to maximize the chemical gradient at half the depth of boundaries between lines and spaces.

Dependence of chemical gradient on half-pitch and optical contrast

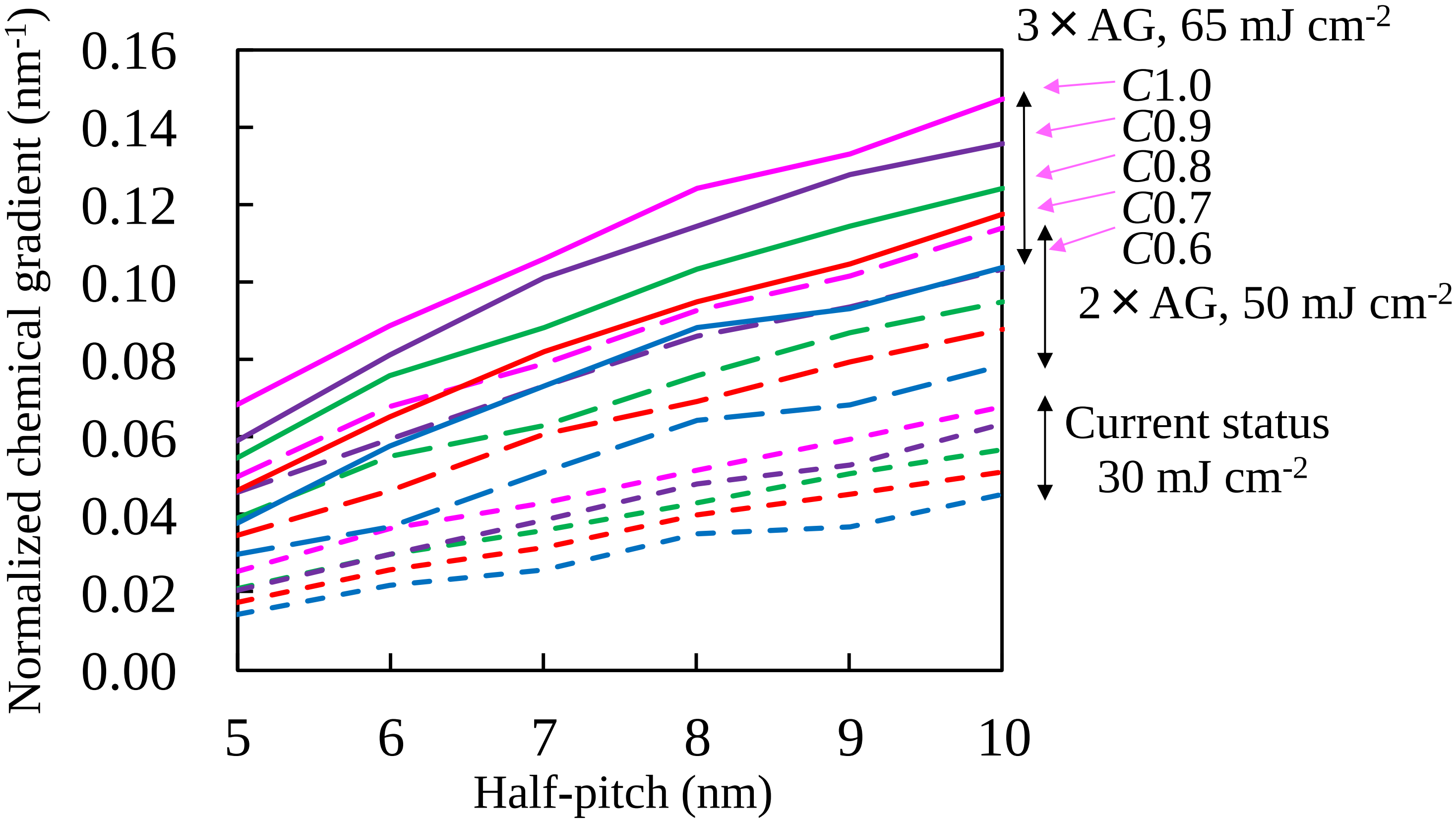


Fig. Dependence of normalized chemical gradient on half-pitch. The numerical values next to C denote the optical contrast. The optical contrast was changed from 0.6 (bottom line) to 1.0 (top line) in steps of 0.1 for each acid generator concentration. The effective reaction radius for deprotection was 0.1 nm.

Dependence of LER on half-pitch

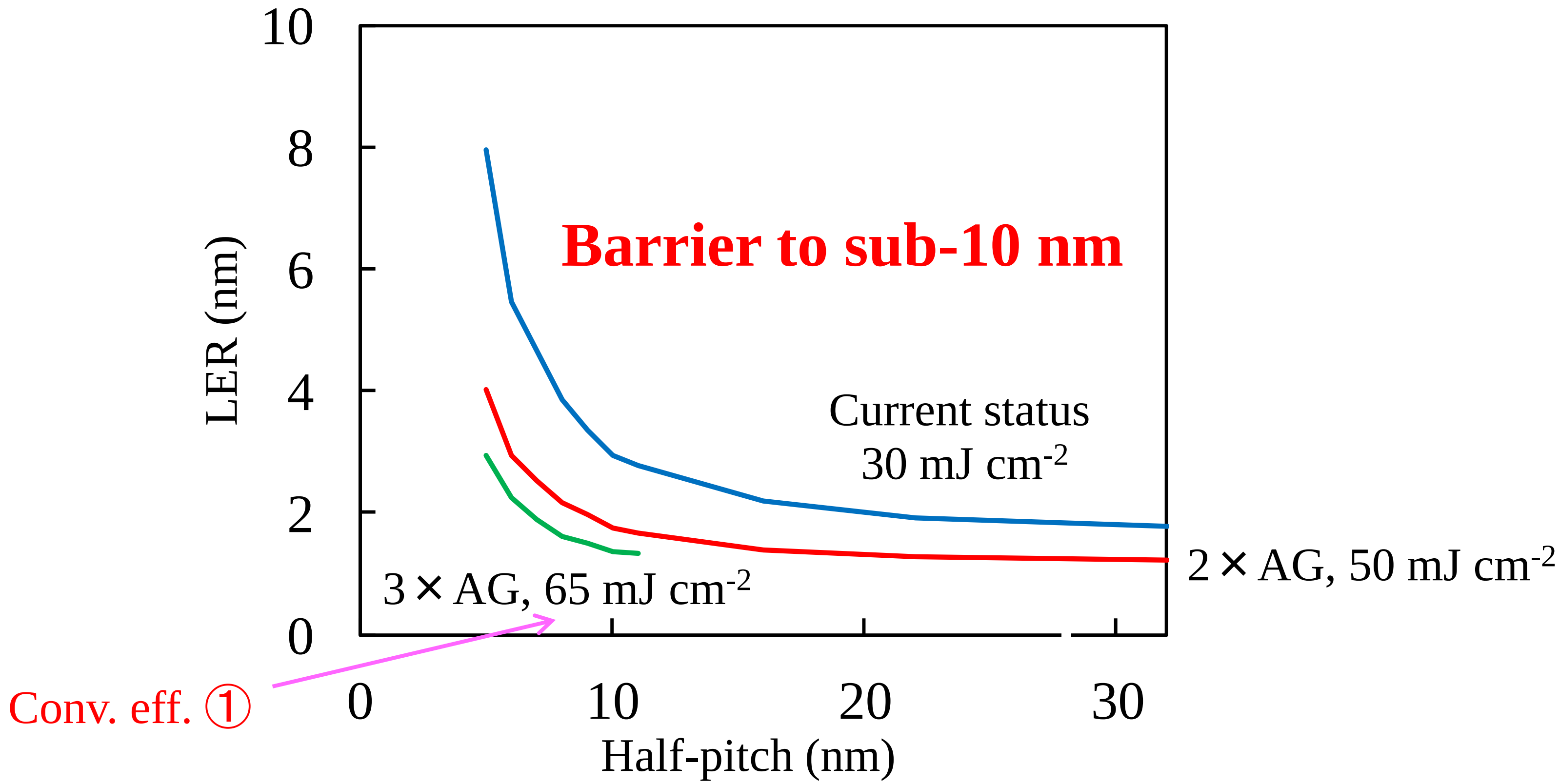


Fig. Dependence of LER on half-pitch. The proportionality constant f_{LER} was 0.2. The optical contrast was 1.0. The effective reaction radius for deprotection was 0.1 nm.

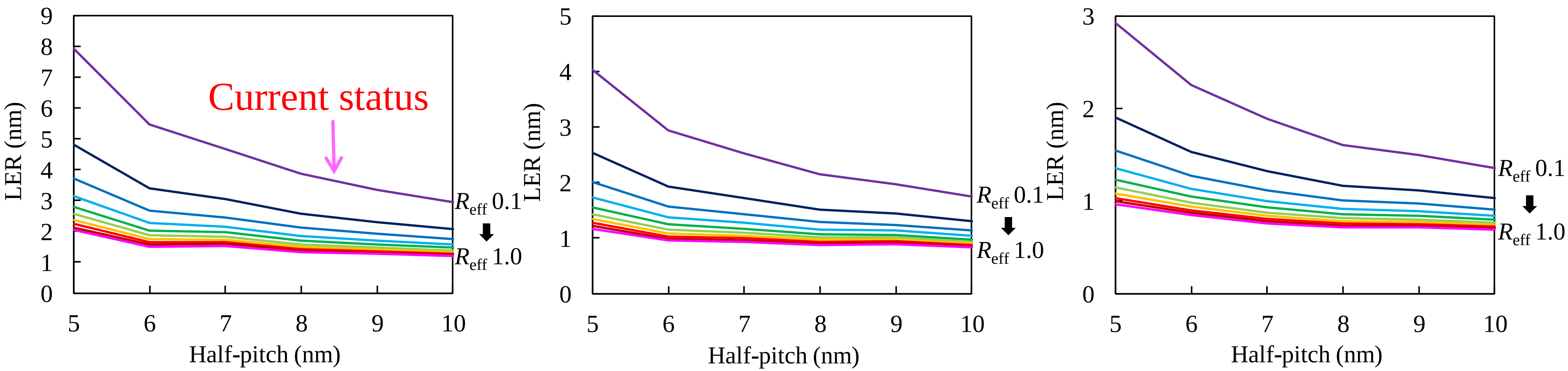
Increase in AG conc. = Increase in the number of interaction points of secondary electrons

Degradation of dissolution kinetics
Conv. eff. ④

Decrease in activation energy for acid diffusion

Decrease in effective reaction radius for deprotection
Conv. eff. ③

Effect of effective reaction radius for deprotection



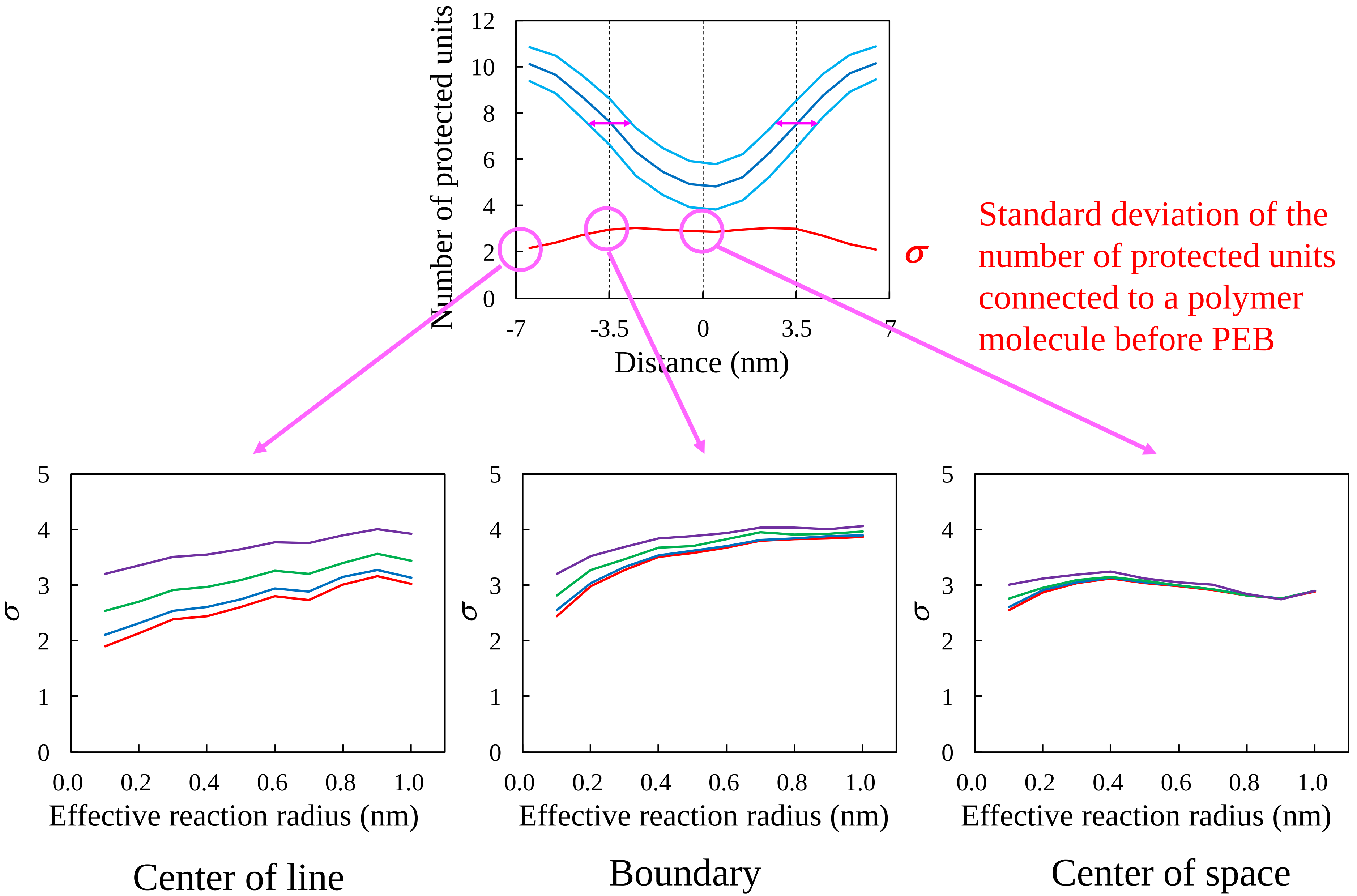
1×AG, 30 mJ cm^{-2} 2×AG, 50 mJ cm^{-2} 3×AG, 65 mJ cm^{-2}

Fig. Effect of effective reaction radius for deprotection on relationship between LER and half-pitch. The numerical values next to R_{eff} denote the effective reaction radius for deprotection in nm. The effective reaction radius for deprotection was changed from 0.1 (top line) to 1.0nm (bottom line) in steps of 0.1 nm. The proportionality constant f_{LER} was 0.2. The optical contrast was 1.0.

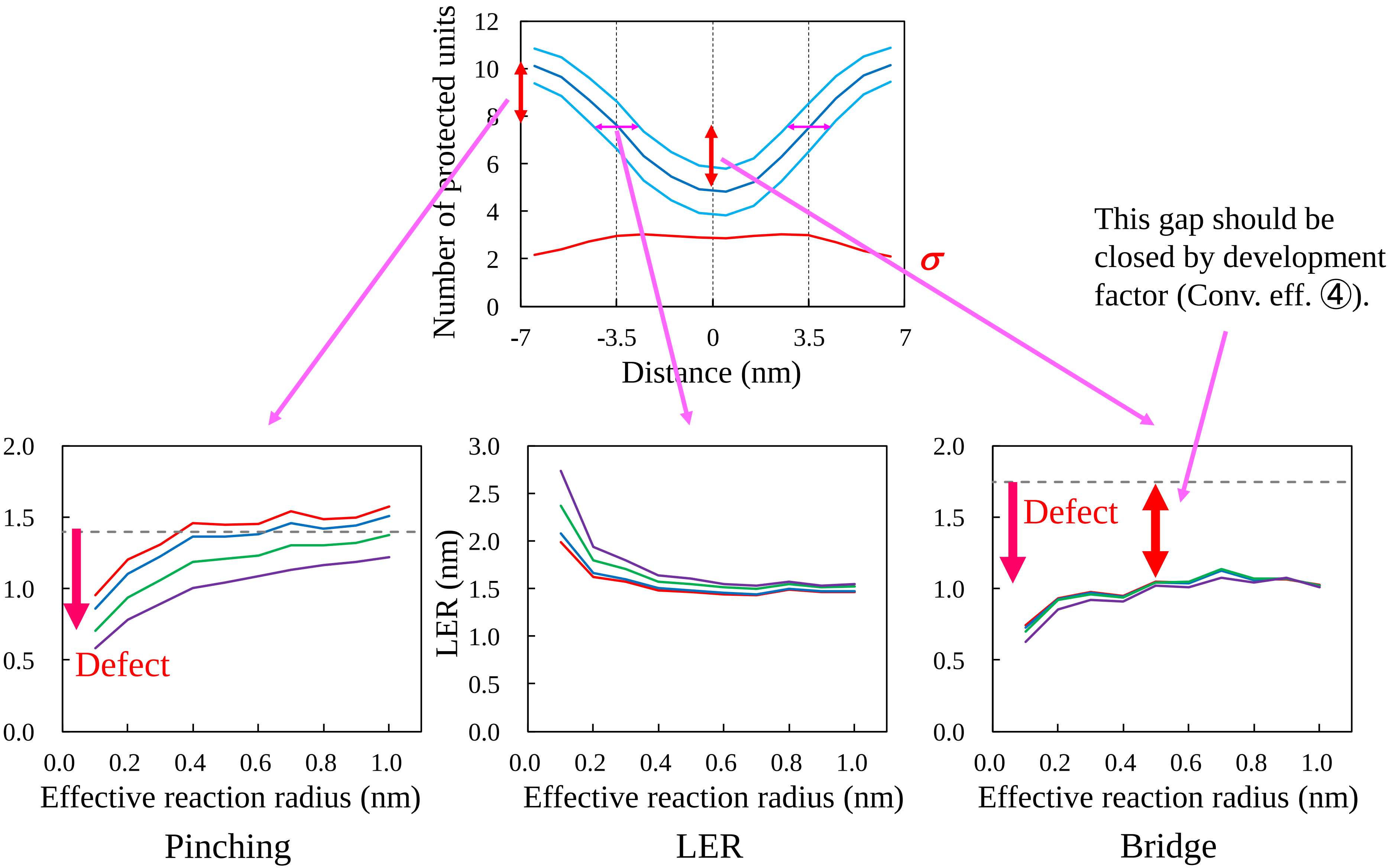
$$LER = \frac{0.68\sigma_n}{dm/dx}$$

f_{LER} was assumed to be independent of R_{eff}.

Fluctuation of number of protected units connected to a polymer molecule



Stochastic effects



Current effective reaction radius: 0.06-0.16 nm

Development target of effective reaction radius: 0.4 nm

Optimum PEB time

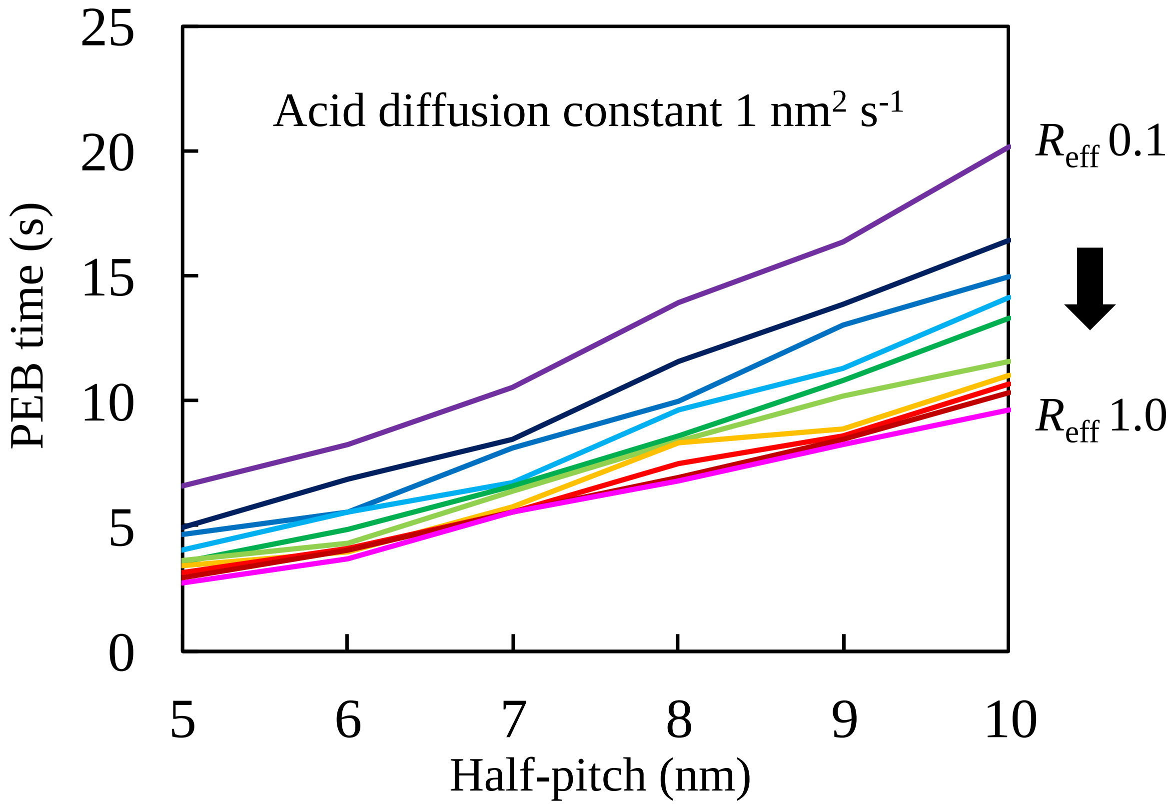


Fig. Effect of effective reaction radius for deprotection on relationship between optimum PEB time and half-pitch. The effective reaction radius for deprotection was changed from 0.1 (top line) to 1.0nm (bottom line) in steps of 0.1 nm. The optical contrast was 1.0.

Current status of acid diffusion constant

2-10 nm^2 s^{-1}

Summary

The feasibility of chemically amplified resist processes for the sub-10-nm half-pitch node was examined, assuming the use of EUV lithography.

1.With a reduction in half-pitch, LER rapidly increased in the sub-10-nm range. Even if a high-resolution EUV exposure tool is developed, there will be a barrier to sub-10-nm fabrication using chemically amplified resists as long as the current performance of chemically amplified resists is assumed.

2.For the realization of sub-10-nm fabrication, an increase in the number of interaction points of secondary electrons in the resist matrix, namely, an increase in the acid generator concentration, is essential. The development of the technologies required for increasing the acid generator concentration without degrading the other conversion efficiencies is important.

Acknowledgement

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Details of discussion can be found in

1. T. Kozawa, J. J. Santillan, and T. Itani,
   Feasibility study of sub-10-nm half-pitch fabrication by chemically amplified resist processes of extreme ultraviolet lithography:
   I. Latent image quality predicted by probability density model,
   Jpn. J. Appl. Phys. **53**, 106501 (2014).
2. T. Kozawa, J. J. Santillan, and T. Itani,
   Feasibility study of sub-10-nm half-pitch fabrication by chemically amplified resist processes of extreme ultraviolet lithography:
   II. Stochastic effects,
   to be submitted to Jpn. J. Appl. Phys.